# IONIZATION INSTABILITY OF A PLASMA IN CROSSED FIELDS

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## Abstract

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# IONIZATION INSTABILITY OF A PLASMA IN CROSSED FIELDS

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A special feature of a weakly ionized plasma is the possibility of changes in its density as a result of ionization and recombination processes. A consequence of this may be the excitation of a specific ionization instability of the striation type in the positive column of a discharge. The mechanism of striations, as is known, is associated with processes of stepwise ionization ([1]).

Another possibility for the development of an ionization instability, as shown by E. P. Velikhov and A. M. Dykhne ([2]), appears in a magnetic field, when the conductivity of the plasma becomes an anisotropic quantity. In this case, drift currents arise in an inhomogeneous plasma and can promote the growth of conductivity fluctuations. The first observations of this instability were reported in ([3]). The same instability also occurred in work on the study of the effective conductivity across a magnetic field ([4]). Our experiment is a continuation of the preceding studies.

The discharge was produced in a rectangular glass tube (100 × 40 × 15 mm), filled with argon (50 mm Hg) and cesium vapor ($3 \cdot 10^{-2}$ mm Hg). The tube, together with a thermostat, was placed in a uniform magnetic field of strength $H = 0 \div 10^4$ oersted. In the tube there were several pairs of electrodes connected into independent discharge circuits. Thus, closure of the Hall current through the external circuit was excluded ($I_{x0} = 0$). The discharge-current density was about 2 A/cm$^2$, and the discharge time constant was $10^{-2}$ s. The main parameters of the discharge plasma were as follows: electron temperature $T_e = 0.22 \div 0.28$ eV; the degree of ionization of cesium did not exceed 30%; the maximum value of the product of the electron Larmor frequency and the mean time of their collisions with atoms and ions was $\Omega_e \tau_e = 10$; the maximum value of $\Omega_i \tau_i \Omega_e \tau_e \sim 10^{-1}$, i.e., the effect of the magnetic field on the ions was absent; the condition $q = d \ln \tau_e / d \ln T_e < 0$ was always satisfied.

In ([5]) it was shown that in such a plasma the state of the gas of free electrons and of electrons at excited atomic levels is uniquely characterized by the electron temperature, and the degree of ionization is determined by the Saha equation with the same temperature. In this case the relaxation time of the electron

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density to its equilibrium value does not exceed $10^{-6}$ s, while the ionization time depends on the rate at which energy is supplied to the electrons. Thus, the energy balance of the electron gas is determined by the supply of Joule heat and by energy losses in elastic collisions of electrons with atoms and ions, as well as by ionization losses. The anisotropy of conductivity, taken into account by the generalized Ohm’ s law, leads to fluctuation currents in an inhomogeneous plasma. Linear theory shows ($^2$) that for $q \leqslant 0$ the Joule energy due to fluctuation currents causes growth of conductivity fluctuations if $\Omega_e\tau_e$ exceeds a certain critical value of order unity. The maximum growth rate of the fluctuations is

$$\gamma = \frac{I^2/\sigma}{\Phi N_e}\Omega_e\tau_e,$$

where $\Phi$ is the ionization potential of the atom, $N_e$ is the electron density, and $\sigma$ is the plasma conductivity. The density inhomogeneities have the form of striations located in a plane perpendicular to the magnetic field (with $I_z = 0$, $k_z = 0$, if $\mathbf{H} \parallel z$). In this case $\tan\alpha = k_x/k_y < 0$, where $k_y$ and $k_x$ are the components of the wave vector along the mean current $\bar{\mathbf{I}}$ and along $\bar{\mathbf{I}} \times \mathbf{H}$, respectively. The magnitude of the angle $\alpha$ is $70 \div 45^\circ$. We have calculated, by linear theory, the stability boundary $(\Omega_e\tau_e)_{\text{cr}}$ and the magnitude of the increment $\gamma$ for a finite size of striations in bounded argon-cesium plasma

**Fig. 1.** Topology of fluctuation currents. Additional release of energy in regions $\mathbf{I}\,\delta\mathbf{I} > 0$ leads to the appearance of striations—a layered structure (ionization instability)

taking into account the degree of ionization and the value of $q$. It follows from the calculation that $(\Omega_e\tau_e)_{\text{cr}}$ increases with increasing degree of ionization and absolute value of $q$. The form of the fluctuation currents and density inhomogeneities is shown in Fig. 1.

In the experiment the following were measured: the electron temperature from the slope of the cesium recombination continuum; fluctuations of the electron density

**Fig. 2.** Photographs of the plasma in a plane perpendicular to **H**. $a$—$\Omega_e\tau_e = 0$; $b$—$\Omega_e\tau_e = 2$; $c$—$\Omega_e\tau_e = 4$; $d$—$\Omega_e\tau_e = 8$. Exposure time 15 $\mu$sec.

$\Delta N_e/\langle N_e\rangle$ from fluctuations of the intensity of the recombination continuum (the radiation was taken out parallel to the magnetic field from an area of about

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Fig. 3

Figure 3: Fig. 3

5 mm$^2$); the mean electric fields—along the mean current $E_y$ and the Hall field $E_x$. The structure of the plasma-density inhomogeneity was studied by means of a pulsed multistage electro-optical converter (EOC). With the aid of the EOC and oscillograms, the time of appearance of the inhomogeneities, their velocity of motion, and the spectrum of oscillations were determined. In the absence of a magnetic field, the plasma in our experiments is always homogeneous. When a transverse magnetic field is imposed on the discharge, density inhomogeneities and fluctuations of the potential. At small $\Omega_e\tau_e$ ($\lesssim 3$) the inhomogeneities have a regular structure, corresponding to the linear theory. With increasing $\Omega_e\tau_e$, inhomogeneities appear on the striations themselves, and then the plasma becomes turbulent (Fig. 2). Along the magnetic field the plasma is essentially uniform.

Figure 3 gives the dependence of the critical value of the magnetic field $H_{\text{cr}}$ on the electron temperature and the value of $(\Omega_e\tau_e)_{\text{cr}}$ calculated from it. The theoretical dependence $(\Omega_e\tau_e)_{\text{cr}}$ is also shown there.

Experimental measurement of the dependence of $\gamma$ on $H$ or $T_e$ under pulsed-discharge conditions was practically impossible, since the time of formation of the discharge in the magnetic field is comparable with, and even greater than, the development time of the ionization instability:

**Fig. 3.** $a$—experimental boundary of the ionization instability in $H$; the hatched region—by $\Omega_e\tau_e$; $b$—boundary calculated from linear theory

**Fig. 4.** Effect of the instability on the effective conductivity of the plasma $\left(\sigma_e = \langle I_y\rangle / \langle E_y\rangle\right)$ across the magnetic field

$$\tau_i = 1/\gamma \sim \frac{1}{\Omega_i}\frac{\Phi}{T_e}.$$

Under the conditions of the experiment the value was $\tau_i \sim 10^{-4}$ sec at $H = 10^3$ Oe. The minimum time, counted from the beginning of the discharge, at which

Fig. 4

Figure 4: Fig. 4

striations arise was likewise about $10^{-4}$ sec in the experiment.

The amplitude of the density fluctuations $\Delta N_e/\langle N_e\rangle$ at $\Omega_e\tau_e \lesssim 3$ (regular structure) reaches 80%. As $\Omega_e\tau_e$ increases, along with large-scale perturbations, small-scale ones are observed, whose amplitude is $10 \div 20\%$.

The size of the striations is of the order of the size of the plasma layer in the direction perpendicular to the current: $kX_0 \sim 1$. This regularity was checked for $X_0 = 0.4 \div 4$ cm; the tube size was not changed in this case.

The spatial spectrum of the density inhomogeneities is strongly anisotropic, except at large $\Omega_e\tau_e$, when the plasma becomes strongly turbulent.

Measurements of the frequency of density and potential oscillations agree with measurements of the velocity of motion of the striations and their size. The oscillation frequency lies in the range $10^3$ kHz; the velocity of motion of the striations is $\sim 3 \cdot 10^3$ cm/sec. The striations move from anode to cathode. The magnitude of the velocity and its direction agree with the theoretical model (7), which explains the motion of the striations by the noncoincidence of the regions of maximum concentration and maximum ionization because of the diffusion field $T_e\nabla N_e/N_e$.

The good agreement of the characteristics of the observed instability with the theoretical ones makes it possible to assert that we are observing an ionization instability of a plasma in crossed $\mathbf{E} \times \mathbf{H}$ fields.

Inhomogeneities of the plasma conductivity in a magnetic field strongly affect its effective conductivity $\sigma_{\mathrm{e}} = \langle J_y\rangle/\langle E_y\rangle$. Figure 4 shows the ratio of the effective conductivity in a magnetic field to the mean conductivity without a field, calculated from the experimental data by the formula $\sigma_{\mathrm{e}}^H/\sigma_{\mathrm{e}}^0 = N_{e0}\tau_{e0}E_{y0}/N_{eH}\tau_{eH}E_{yH}$, as a function of $\Omega_e\tau_e$. Here the change in the electron density and in the frequency of their collisions with changing $T_e$ in the magnetic field was taken into account. The measurements showed that the ratio $E_x/E_y$ becomes saturated at the level 2 and does not change for $2 < \Omega_e\tau_e < 10$ (analogously to (4)). These results are in good agreement with the results obtained by Vedenov and Dykhne [6].

It is interesting to note that the process of transition from the laminar state to the turbulent one, observed in the case of an ionization instability that is aperiodic, is analogous to the process of turbulence development in ordinary hydrodynamics (L. D. Landau). The excitation of the fundamental mode at small supercriticality $\Omega_e\tau_e$, the stability of this mode at large amplitude of the plasma-density fluctuations, the destruction of the fundamental mode, and the turbulization of the plasma as $\Omega_e\tau_e$ is increased are reminiscent of the well-known picture of the development of Bénard cells and Taylor vortices.

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